

Aircraft Vortex Spacing System (AVOSS) Conceptual Design

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Abbreviations

AGL	Above Ground Level.
ASR	Airport Surveillance Radar.
ATC	Air Traffic Control.
AVOSS	Aircraft Vortex Spacing System.
CFD	Computational Fluid Dynamic.
CTAS	Center-TRACON Automation System.
D	Distance from landing runway.
DA	Descent Advisor.
FAST	Final Approach Spacing Tool.
GS	Glide Slope.
ILS	Instrument Landing System.
IMC	Instrument Meteorological Conditions.
ITWS	Integrated Terminal Weather System.

MEM	Identifier for Memphis International Airport.
NTSC	National Transportation Systems Center.
ORD	Identifier for Chicago O'Hare Airport.
PBL	Planetary Boundary Layer.
RASS	Radio Acoustic Sounding System.
TAP	Terminal Area Productivity.
TASS	Terminal Area Simulation System.
TERPS	United States Standard for Terminal Instrument Procedures.
TMA	Traffic Management Advisor.
TRACON	Terminal Radar Approach Control.
VMC	Visual Meteorological Conditions.

Purpose

The purpose of this document is to provide a system concept for the development of an Aircraft Vortex Spacing System (AVOSS). The AVOSS will use available knowledge of aircraft wake generation, atmospheric modification of those wakes, wake encounter dynamics, and operational factors to provide dynamical wake vortex spacing criteria for use by Air Traffic Control. Only the concept for the AVOSS will be provided. In some sections assertions will be made that are based on preliminary, unpublished efforts or discussions with other wake vortex researchers and meteorologists. These assertions will be validated prior to being used in any prototype system. The data required to establish precise system requirements and performance levels will be produced during the research and development efforts. It is hoped that this description of the AVOSS concept will help direct the necessary research and field programs to produce a demonstration prototype AVOSS.

Introduction

A continuing trend for increased air travel, combined with severe environmental restrictions on expansion or new airport construction, has led to more frequent flight delays and associated costs to the traveling public and to the air carriers. One response has been an increased interest in maximizing the efficiency of the runway capability that is available. The National Aeronautics and Space Administration is addressing the problem through its Terminal Area Productivity (TAP) Program. The major goal of the TAP program is to provide the technology base and systems to permit the same airport capacity levels during instrument operations that are presently experienced during visual airport operations. Under current airport operations a degradation in weather conditions from clear to poor seriously degrades capacity due to numerous factors. These factors include reducing the number of available runways, increased time required for an airplane to decelerate and taxi clear of a runway after landing, and wake vortex separation constraints used by air traffic control (ATC) in the spacing of aircraft to a runway. Two major initiatives under TAP are the development of advanced ATC automation tools and wake vortex systems to improve terminal area efficiency and capacity. NASA Ames is the responsible center for development, testing, and demonstration of a Center-TRACON Automation System (CTAS), reference 2, which includes a Traffic Management Advisor (TMA), a Descent Advisor (DA), and a Final Approach Spacing Tool (FAST). This automation provides aids to the controller to effectively schedule and sequence arrivals and minimize variations in desired interarrival spacing. This automation provides an opportunity to dynamically alter the wake vortex separation constraint as a function of the weather and the actual aircraft pair type (as opposed to broad weight categories). NASA Langley is performing the research and development to develop the automated wake system, known as the Aircraft Vortex Spacing System (AVOSS).

The impact of wake vortex on aircraft separation standards under instrument conditions results from multiple factors. During instrument flight conditions ATC has direct responsibility for aircraft separation. Under visual conditions responsibility for separation may be given to the pilot during the

final approach phase. In this situation the pilot visually acquires the lead aircraft and the airport, is authorized for a "visual approach", and follows the lead aircraft to the landing runway. When ATC is responsible for separation either radar separation or a fixed wake separation criteria is applied, which is a function of the weight classification of the two aircraft. When the pilot is responsible for separation the primary constraint on following distance in many situations is the time interval required for the leading aircraft to taxi clear of the landing runway prior to the landing of the following aircraft. The pilot applies the separation distance that he or she believes is appropriate to the aircraft being followed and the weather conditions. The significant difference between the criteria applied by ATC and applied by the pilot is that the ATC constraints do not vary with wind and turbulence levels. The separation must therefore be based on worst case weight differences between and within aircraft weight categories and wake persistence observed during weather conditions favorable for long vortex life. For example a transport aircraft weighing 200,000 pounds must be given the same separation behind a 15,000 pound business jet as would be required if the business jet were following the transport. Pilots, however, will generally provide greater separation under weather conditions conducive to wakes persisting on the approach path than they will provide under high turbulence or high cross wind conditions that favor rapid wake dispersal. During visual approaches pilots routinely follow other aircraft much closer than the distances specified by the ATC criteria, with no adverse effects from the lead aircraft wake. To date the scientific basis does not exist to quantify the wake transport and decay properties and aircraft pair interaction dynamics with sufficient accuracy to incorporate weather dependent ATC separations, that are significantly different from current standards, into actual use.

As an element of the TAP program, and in support of the FAA Integrated Wake Vortex Program Plan (reference 3), NASA Langley Research Center is beginning the development of an Aircraft Vortex Spacing System (AVOSS). The purpose of the AVOSS is to integrate current and predicted weather conditions, wake vortex transport and decay knowledge, wake vortex sensor data, and operational definitions of acceptable strengths for vortex encounters (acceptable vortex strength definition) to produce dynamical wake vortex separation criteria. By considering ambient weather conditions the wake separation distances can be relaxed during appropriate periods of airport operation. With the appropriate interface to planned ATC automation (CTAS), spacing can be tailored to specific generator/follower aircraft types rather than several broad weight categories of aircraft. In a manual ATC, a simplified form of the AVOSS concept may be used to inform ATC when a fixed alternate, reduced separation standard may be used for the "large" and "heavy" aircraft categories. The purpose of this document is to describe the concept and candidate form of an operational AVOSS system, system ground rules and requirements, research needs, and the development efforts being followed. This document should form the basis for concept refinement and coordination/interaction of individual research efforts to implement a solution.

Prior Research

The AVOSS prototype development will build on prior wake vortex research activities conducted by the FAA, Volpe National Transportation Systems Center, and industry. In particular, reference 1 provides a system concept that forms the foundation of the current system development. Since that system concept was defined many advances in computational fluid dynamic modeling, weather sensors, and ATC automation have occurred which are expected to enable a practical implementation of an Aircraft Vortex Spacing System. A detailed bibliography of prior research activities and a summary of the knowledge gained can be found in references 4 and 5.

Much of the previous research considered the wake vortex to be primarily a characteristic of the airplane type, and hence field experiments rarely collected a comprehensive set of meteorological data. Also, little data exists to document decay characteristics in ground effect or the behavior of vortices that are generated at altitudes less than the wingspan of the generator. The present effort includes a strong meteorological component in evaluating vortex behavior and will attempt to collect vortex data at all altitudes of operational significance.

AVOSS Concept

The philosophy behind the AVOSS system is to avoid aircraft encounters with vortices above an "operationally acceptable strength." This avoidance is obtained through consideration of two primary factors, wake vortex motion away from the flight path of following aircraft and wake vortex decay. Since these factors are highly dependent on ambient meteorological conditions, as well as the generating aircraft position and type, the wake vortex constraints on aircraft separation are expected to vary significantly with the weather. Since metering to meet airport acceptance rates occurs back in center airspace while aircraft separation on final approach is determined during the vectoring and descent process as aircraft enter the initial approach area, the AVOSS system must provide a predictive capability to realize reduced approach spacing. Initial predictions of wake vortex separation constraints 30 to 50 minutes in advance of the actual approach is required to take full advantage of reduced wake constraints. This predictive requirement will drive all efforts in the primary work areas of meteorological sensors, wake sensors, ATC procedures, and system architecture. Avoidance will take the form of providing manual or automated ATC systems with a matrix of permissible aircraft spacing, from a wake vortex perspective, with sufficient advance time and stability for use in metering aircraft to the final approach fix.

The potential for an encounter will be determined through consideration of vortex motion and boundaries of the corridors used by the aircraft. Since the AVOSS must predict minimum safe aircraft spacing well before the aircraft have begun the final approach segment, some assumptions must be made about the paths to be flown if vortex motion is to be used as a separation constraint. During approach, the corridor boundaries may be defined by the FAA criteria for obstacle clearance under the philosophy that a vortex of any strength outside that corridor is at least as acceptable as a solid object at the same location. This criteria is extremely conservative, as will be discussed below, and FAA/industry consensus may be reached on more realistic boundaries based on observed statistical aircraft deviations from the final approach localizer/glide slope. While AVOSS can be designed to any specified criteria for the approach and departure corridors, the choice will affect the capacity gains that can be realized.

Prior research (reference 1) suggests that vortex motion is influenced by the altitude of the vortex above the ground, even if subjected to an identical wind condition at all altitudes. This factor, combined with the knowledge that atmospheric wind conditions also change with altitude will require that the AVOSS consider motion and decay at a range of altitudes along the approach path from near glide slope intercept to the runway. The altitude or location on the approach with the longest lasting hazard will determine the separation required for the entire approach.

The term "operationally acceptable strength" indicates that vortex encounters will be permitted if the strength of the encountered vortex will have no adverse operational effect (pilot or passenger concern, increase in touchdown point dispersion, need to disengage autopilot, etc.) on the trailing aircraft. Such would be the case, for example, of a 600,000 pound transport encountering the wake of a 13,000 pound business jet. While the research will define "operationally acceptable strength", it is safe to assert that this strength will be well below the strength required to produce an upset. FAA and industry consensus will be essential to the establishment of this strength limit.

The general AVOSS structure is shown in figure 1. The meteorological subsystem provides current and expected atmospheric state to the predictor subsystem. The predictor subsystem, to be discussed in detail below, utilizes the meteorological data, airport configuration, and aircraft specifications to predict the separation time required for a matrix of aircraft. The sensor subsystem monitors actual wake vortex position and strength to provide feedback to the predictor subsystem and to provide a warning to ATC if a spacing is sufficiently in error to require a wave-off.

Ground rules must be established in order to begin the development of an AVOSS. The ground rules for the AVOSS are as follows.

1. The development effort will be focused on a system that can be approved for operational use. This will require a large degree of robustness, reliance on readily available meteorological and wake sensors, graceful system degradation when sensors or subsystems fail, and cost realism.
2. The safety provided will be equal to or greater than the currently operational system. Safety margins must be consistent with current aviation standards. As an example, when vortex transport is the critical factor used to establish spacing, the required distance from the following aircraft to the vortex must consider expected flight technical error in the aircraft trajectories.
3. The AVOSS will not require an increment in pilot skill levels or training requirements. While improved AVOSS performance would be likely if very small flight technical errors could be assured, the AVOSS will be designed around the flight technical errors that currently exist. Likewise special pilot training might increase the vortex "operationally acceptable strength" that could be encountered, but that approach is not considered practical due to serious safety, pilot certification, public acceptance, and training cost issues.
4. No aircraft structural or systems modifications will be required. Although various aircraft modifications might increase the vortex decay rate, the modifications would produce little airport capacity increases until the current fleet has been replaced, or modified at high cost. Likewise improved flight control systems or high authority autopilots with wake encounter algorithms might increase the vortex "operationally acceptable strength" that may be encountered. These changes would likely have a prohibitive cost when safety, certification, and aircraft retrofit are considered. If future aircraft are built with systems that minimize the wake, however, the envisioned AVOSS could take advantage of that aircraft feature.
5. The AVOSS will not alter current pilot/controller roles and responsibilities. The ATC system will continue to meter and space aircraft into the terminal area and final approach paths, using AVOSS supplied information. The overall system architecture and safety considerations must be acceptable to the airline industry and the pilot community.
6. "Vortex-limited" spacing operations may require special ATC or flight procedures compatible with current skill levels. Examples may include executing straight-in ILS approaches, no intentional operations above glide slope, or vectoring aircraft to the final approach fix with heavier aircraft downwind of lighter aircraft. The envisioned AVOSS could function without these special operational procedures, but the capacity gain would be greatly reduced due to larger uncertainties in expected aircraft location.
7. The AVOSS system must provide meaningful increment in airport capacity in IMC and not reduce capacity in VMC. Although there will almost certainly be time periods when the AVOSS will not increase capacity, due to the existing meteorological conditions, it is expected that there will be periods when spacing can be significantly reduced. During AVOSS development, system tradeoff studies will be performed to assess the potential capacity gain. These studies will be airport specific and will require detailed climatology data, the wake vortex behavior predictor algorithms under development, assumptions about acceptable spatial and vortex strength buffers, the performance of potential weather sensors, the traffic mix for that airport, and arrival schedules. A criteria for utilizing AVOSS at a particular airport is likely to be demonstration, via simulation or prototype demonstration, that the AVOSS will significantly improve capacity during capacity limited periods on a frequent basis.

As suggested above, the AVOSS system and ATC interface will require both technical processes and integration with operational practices. The technical aspects include understanding of vortex behavior under various atmospheric conditions, aircraft encounter dynamics, and the sensor systems required. The operational aspects include runway configuration and usage at a specific airport, the aircraft mix arriving during peak traffic periods, procedures for vectoring aircraft to the localizer, and the use of visual or instrument approaches. The operational factors must be considered in the AVOSS implementation. For example, when all aircraft are constrained to full ILS approaches the precise knowledge of expected aircraft trajectory may allow AVOSS to provide the minimal spacing. When visual approaches are in use the relative uncertainty in aircraft trajectory may require reversion to a default spacing, or a less optimum spacing based only on vortex decay rates. Likewise the potential for a pilot to fly above the glide slope during approach, or to revert to a

"localizer" approach following a glide slope receiver failure, may require special ATC notification to pilots and procedures when the AVOSS-provided minimal spacing is in use. This potential has precedent, in that pilots are advised today when simultaneous parallel approaches are in use and use additional care to ensure that the localizer capture is precise. In the AVOSS case this may require ATC notification of "Minimal spacing operations in effect".

Predictor Algorithm Requirements and Architecture

The core of the AVOSS system is the "predictor algorithm". This algorithm will accept weather state, a matrix of generating aircraft characteristics that relate to initial wake strength, dimensions of the operational corridor, and a matrix of limiting vortex strength for encounters with following aircraft. This data will be used in real-time to predict the interarrival time interval required, by the wake vortex constraint only, for each aircraft pair in the aircraft matrix. When weather conditions predicted to exist 20 to 50 minutes in the future are input, the predictor algorithms will provide the required spacing at that time. Uncertainty in weather state estimation and aircraft parameters must also be considered to provide an appropriately conservative separation prediction. The ATC system will use this data along with other constraints such as runway occupancy time and radar control precision to establish actual aircraft pair spacing. Two prediction horizons are required, an initial prediction for flow rate metering and a shorter time prediction for the CTAS FAST or approach and final controller use.

The following candidate requirements for the predictor algorithm are suggested. The adequacy of these early requirements will be substantiated or changed as required during the development process.

1. The predictor algorithm must provide separation of aircraft from significant vortices along the entire final approach path, from glide slope intercept to the runway. This range is needed due to the differences in vortex behavior at various altitudes. The required aircraft separation must be predicted for a series of "windows" along the approach path. An approximately logarithmic altitude selection is suggested, with windows spaced to intersect the approach path at altitudes of 25, 50, 100, 200, 400, 800 feet, and the glide slope intercept altitude. The research required for development may indicate the need for greater or fewer windows.
2. The predictor algorithm is only required to accurately predict vortex behavior for aircraft separation times equivalent to the minimum runway occupancy time of about 40 seconds or more. Early efforts suggest that many atmospheric conditions may transport the vortices away from the path of following aircraft in as little as 20 or 30 seconds (reference 1). While validation of these situations is required, little additional research could be justified to refine predictor performance in this domain. As predicted wake constraints exceed runway occupancy time, however, great care is required to establish predictor performance and uncertainty intervals.
3. The predictor algorithm must function without detailed knowledge of aircraft approach flap setting, airspeed, or weight. Only aircraft type and whether the operation is a takeoff or a landing will be used. The reason for this requirement is that predicting aircraft speed, weight and configuration 30 minutes in advance would require mandating speeds for the crews and/or a modification to procedures and systems to permit data link of each aircraft operating weight and planned approach configuration to the ATC system. This violates the proposed ground rules. Since the predictor algorithm will not have complete knowledge of aircraft initial wake conditions the predictions provided will be based on the potential range of initial wake conditions. This should not incur a severe penalty on the system, since transport aircraft generally fly similar speeds in high density operations and most operators will use a narrow range of flap settings for a particular operation.
4. The prediction algorithms will not be dependent on a simple 3 or 4 element matrix of aircraft weight categories. The aircraft matrix given to the prediction algorithm should contain an entry for as many individual aircraft types (i.e. MD-11, B-737-300) as possible. The wake spacing constraint can then be predicted for each pair of aircraft types. An ATC automation aid such as CTAS can use this information combined with the scheduled arrival sequence to provide individual spacing. AVOSS could collapse the full aircraft matrix into a smaller matrix in real-

time for use by manual ATC facilities. The potential also exists to run the predictor algorithms off line to refine existing aircraft categories and separation standards.

5. The predictor algorithm must accommodate feedback from wake vortex sensors. The sensed wake behavior will be used to ensure system safety through mechanisms such as increasing uncertainty buffers when the wake behavior deviates from predictions, to revert to a default spacing criteria when a threshold of prediction errors is crossed, or to provide a time critical alert to ATC if a wake persists long enough in the corridor to be a hazard to the following aircraft. The anticipated system will combine weather-based predictions with wake sensor feedback to reduce the level of uncertainty.
6. The predictor algorithm must be based on wake vortex knowledge that is or will be available in the near term, while accommodating increments in this knowledge. For example, an early AVOSS may function for single runway configurations with simple vortex motion estimation models yet provide predictions for intersecting or parallel runways when vortex motion estimation models are improved. An early AVOSS may significantly improve airport capacity in some weather situations using vortex transport models only, which are currently more mature than decay models, and further improve capacity when the decay models and aircraft encounter dynamics are established.
7. The operational domain of the AVOSS will be the approach corridor and the initial climb corridor only. The purpose of AVOSS is not to reduce the number of wake encounters that currently exist in the initial descent and terminal area regions before beginning the approach. Due to the requirement to compare vortex motion to expected following aircraft position, relatively uncertain predictions of aircraft position in the terminal area, and limitations in the meteorological data available throughout the terminal area, operational procedures alone will be used above altitudes of about 1600 feet AGL for wake purposes. Examples might be merging aircraft onto the localizer from alternating entry points, with assigned altitudes that are mandatory rather than minimum. This should not be significantly different than current terminal area operations, since runway occupancy time is already the limiting spacing factor during visual operations in some situations. Close cooperation between NASA and FAA Air Traffic and Flight Standards will be required during this effort to define acceptable operational procedures for AVOSS development.
8. The vortex "operationally acceptable strength" definition required for AVOSS must provide an accurate value for permissible encountered wake strength for commuter and transport category aircraft, but not for smaller general aviation aircraft. Since the traffic mix at capacity constrained terminals is heavily dominated by transport aircraft, very little overall capacity gain can be expected from detailed study of the initial wake and wake encounter dynamics of the smaller aircraft. Application of conservative standards for these aircraft is suggested, although limited research may be required to arrive at this standard. Prediction of wake motion and decay from "small" aircraft (less than 12,500 pounds maximum gross weight) is also not required for an effective AVOSS. There is no reason to believe that wakes from these aircraft affect airport capacity at major terminals during high traffic periods.
9. The predictor algorithms must function in a sufficiently wide range of airport and meteorological conditions to improve airport capacity, but are not required to function in all conditions. Under conditions that do not permit accurate wake vortex predictions the AVOSS may provide existing manual ATC separation criteria as the "default" spacing.

Given the basic predictor algorithm requirements, the structure of the predictor algorithms are suggested. Figure 2 shows the expected structure. The predictor subsystem will ingest meteorological data and projections, an aircraft specifications matrix, and airport configuration data. The meteorological data and projections will not only include the actual parameters of interest, but must also include the confidence intervals on those parameters. By combining meteorological data and airport configuration data the predictor will establish data such as headwind and crosswind components along each approach path. Alternatively a requirement could be placed on the meteorological subsystem to provide specific data at specified spatial locations along the approach and departure corridors.

The aircraft matrix will include that data required for each operational aircraft type to predict the initial wake characteristics. The first order wake data expected to be required includes the spacing of the wake cores and total circulation strength. First order estimates of these values can be calculated from aircraft wing span, weight, speed, and air density. Other factors, such as flap setting also affect the initial wake structure but initial examination of wake data, taken from a B727, B757, and B767 during tower flybys at Idaho Falls in 1990 (reference 6) suggest that a close approximation to the initial behavior can be estimated from span, weight, and speed alone. Further research, some of which is described below, is needed to assess the need for detailed configuration data and more refined initial wake estimates. Initial AVOSS predictor algorithm development will proceed under the hypotheses that basic aircraft parameters are adequate for estimating the initial wake characteristics. Under this assumption the speed of the aircraft can be predicted based on a nominal approach speed for the aircraft type and the speeds actually being used on final during the high traffic period.

The weight of the aircraft could be predicted based on certified maximum landing weight of the aircraft type. While this provides a conservative estimate of vortex strength, it may not provide a conservative estimate of the time required for the vortex to clear the approach corridor. At lighter weights a weaker vortex is produced that may take longer to sink below the flight path of a following aircraft. For this reason the predictor also needs a lower bound for the aircraft weight. One technique would be to use a reasonable minimum aircraft weight based on no cargo and minimum fuel. A more realistic approach may be to collect actual weight data by aircraft operator and aircraft type at each terminal and provide the predictor with a statistical bound of possible weights. For example, a sample of over 1000 aircraft of the same type landing at one major terminal showed all actual landing weights between 57% and 83% of the maximum certified landing weight for that aircraft type. If statistical data of this type is used by AVOSS then an effort may be required, in cooperation with the operators at each major terminal, to determine fleet weight distributions for arrival and departure. A disadvantage of this technique is a possible need to alter AVOSS parameters at a specific terminal if an operator changes route structures or schedules in a way that affects the weight distribution.

After ingesting the required meteorological and aircraft data, the predictor will perform a set of computations for each of the "windows" along the approach path. The first set of computations will determine, for each aircraft type, the time required for its vortices to exit the approach corridor. Consistent with the terminology of reference 1, this time is referred to as the "transport time" for the vortex in that window. Second, the predictor will determine the time required for the vortex of each aircraft to decay below a specified acceptable encounter strength for each following aircraft type. This calculation is also performed for each window along the approach and the time is referred to as the "decay time". This calculation requires, in addition to the meteorological and initial wake estimations, an acceptable vortex strength definition against which vortex strength can be compared. Next, the predictor compares the transport time and decay time for each aircraft pair at each window and takes the minimum value as an acceptable aircraft time spacing. This time is referred to as the vortex "residence time" at each window. Finally, the predictor compares each window residence time and chooses the maximum value as the predicted acceptable time spacing for the entire approach.

If perfect meteorological data and aircraft wake predictions could be generated, this time could be used directly by the ATC system for spacing. Many potential error sources exist, however, and must be considered in the spacing. Figure 3, replicated from reference 1, illustrate two potential error sources. This chart shows an analytical prediction of the time required for both vortices to clear a 300 foot wide approach corridor as a function of the cross wind speed. The generating aircraft is a B747-200, at three different weights, on the glide slope at the middle marker location. The figure shows that in calm winds both vortices clear the corridor in about 60 seconds, in cross winds of about 4 to 7 feet per second the vortices are stalled in the corridor beyond the maximum 120 second period plotted, but in 10 foot per second cross winds the vortices are no factor after only about 25 seconds. Any prediction or actual measurement of wind values will contain some error, with errors growing as the prediction time interval or spatial variations grow. If the cross wind is predicted to be zero at some future time the predictor may provide a 60 second transport time for this window, but

the buffer required to accommodate a 4 foot per second cross wind confidence interval will require a wake constraint of well over 2 minutes to be provided to ATC. Likewise a 12 foot per second cross wind forecast with a 4 foot per second confidence interval would produce a transport time prediction of roughly 20 seconds and the uncertainty would add only 20 seconds to the separation required. Aircraft weight can also be seen to add uncertainty to the prediction. Other error sources include possible flight technical error (deviations from localizer or glide slope) of the leading aircraft, speed changes, and factors such as uneven terrain or land/water interfaces along the approach. The resultant requirement is for the prediction algorithm, as well as the meteorological subsystem and the initial aircraft parameter matrix, to provide confidence intervals on all parameters so that the final product delivered to ATC provides the necessary error buffers.

Approach Corridor Dimensions

The corridor to be protected will be subject to FAA and industry consensus. Although the most general case of a corridor would call for a completely "open sky", that is visual curved approaches to a runway, such a wide corridor would defeat the purpose of the AVOSS transport predictions and fail to utilize the AVOSS capacity gains possible under true instrument approach operations. While future instrument curved approaches can be accommodated normally by AVOSS, visual curved approaches may require reverting to the default spacing criteria presently in use or temporarily disabling the transport rule component of AVOSS. The most conservative feasible buffer is the approach obstacle clearance criteria specified in reference 7. This manual specifies an obstacle clearance plane that begins 200 feet from the runway threshold at an altitude of zero and a width of 1000 feet. The width of the clearance plane floor increases such that the total width is 4000 feet at a distance of 10,200 feet from the runway and 16,000 feet at a distance of 50,200 feet from the runway. The width of this corridor would impose a severe constraint for wake vortex drift. The altitude of the clearance plane typically increases with a slope of 50:1 out to a distance of 10200 feet from the runway, then at a slope of 40:1.

In the example and tables to follow the glide slope angle is assumed to be 3 degrees, the middle marker location is located at the point where the glide slope altitude is 200 feet above the runway elevation (2816 feet from the runway), and the outer marker to be 5 miles or 30390 feet from the runway. The glide slope intercept point is assumed to be 1000 feet from the runway threshold.

Using the TERPS corridor width and a lateral drift of 10 knots for the vortex, the transport time would be about 30 seconds at the runway threshold, about 53 seconds at the middle marker, and over 130 seconds at a window 2 miles from the runway. At the outer marker location the transport time due only to lateral vortex motion would be nearly 5 minutes. The transport time due to vortex sinking is more realistic. Due to uncertainties in vortex sinking and "bouncing" in ground effect only lateral motion will initially be considered inside the middle marker. At the middle marker position the obstacle plane is about 143 feet below the glide slope and about 57 feet above the ground. At a vortex sink rate of 500 feet per minute, and neglecting ground effect, the vortex would sink below the obstacle plane in only 17 seconds, compared to the 53 seconds required for lateral clearance with a 10 knot drift. At a position 2 miles from the runway the obstacle plane is about 435 feet below the glide slope and the vortex could sink through this altitude in about 52 seconds, compared to the 130 second lateral motion example given. At the outer marker the obstacle plane is about 935 feet below the glide slope and the time required for the vortex to sink, neglecting decay and other atmospheric effects, is about 112 seconds. Given a more conservative vortex sink rate of 200 feet per minute, the time to sink below the corridor at the middle marker, 2 miles, and the outer marker is 43, 131, and 281 seconds respectively. Note that the vortex sink rates and clearance times given above are not being suggested as parameters in an AVOSS predictor. These are only examples and the actual atmospheric and ground effects on vortex drift and sink must be determined and validated at these various altitudes.

Two conclusions can be reached from the above discussion. The first conclusion is that, at most locations on an ILS, sinking of the vortex pair may frequently provide a mechanism for permitting reduced spacing. This is consistent with operational experience as documented by the British wake

vortex reporting system (reference 8). Relatively few wake encounters take place during the initial portion of the approach while on glide slope, but many occur at relatively low altitudes of about 100 to 300 feet. Second, the obstacle clearance plane may be overly conservative for this purpose. While an obstacle near the approach path has a probability near unity of always being there, a vortex can move outside the corridor in any direction and has a much lower probability of being in the same location as an aircraft that has also deviated from the corridor.

For AVOSS development a more appropriate protection corridor may be defined from considerations of previous wake vortex efforts, actual flight technical error observed in service, and the limits of the ILS path itself. For example, reference 1 defined a corridor width of 300 feet (150 feet each side of the runway centerline) from the middle marker to the runway. This was based on statistical data showing 3- σ aircraft variation from centerline at the middle marker to be about 50 feet and research showing that a vortex separated laterally from the aircraft by 100 feet "cannot significantly affect aircraft motion". No suggestion was given in that paper for lateral separation outside the middle marker.

Statistical data such as that shown in reference 9 can be used to estimate appropriate corridor sizes outside the middle marker. This report provides statistics on observed aircraft dispersion about the runway centerline at various distances from the runway, both at Memphis and Chicago. At Memphis the average distance from centerline at two miles from the runway was 18 feet with a standard deviation of 73 feet (sample of 968 arrivals). At 5 miles from the runway the average distance from centerline was 29 feet with a standard deviation of 144 feet (982 arrivals). At Chicago at 2.1 miles from runway the average distance was 22 feet with a standard deviation of 84 feet (1903 arrivals) while at 5.1 miles the average and standard deviation were 15 feet and 133 feet respectively (2070 arrivals).

Finally, full scale widths of the ILS system suggest corridor limits. The glide slope system saturates at an angular error of 0.7 degrees from center. At the outer marker this translates into an altitude error of about 380 feet. The localizer width is tailored to provide a width of 700 feet at the runway threshold. For a 6000 foot runway this produces an angular width of about 6 degrees. At the outer marker the total corridor width would be about 3900 feet. For a 10,000 foot length runway the localizer angular width is about 3.8 degrees. At the outer marker the total corridor width would be about 2700 feet.

Table 1 summarizes the corridor widths suggested by the techniques discussed above and suggests a candidate corridor width for AVOSS development purposes. The "TERPS" column presents the dimensions of the FAA-required obstacle clearance surface and the "Reference 1" column presents the dimension suggested by the earlier work of reference 1. The "Lincoln ASR" column represents three standard deviations of the observed radar data plus 100 feet. The "ILS" column represents full scale deflection of the localizer indication assuming a runway length of 8000 feet. The table entries assume a glide slope angle of 3.0 degrees. The "AVOSS" column is the recommended AVOSS protected corridor width. The width of the AVOSS corridor is roughly 6 to 7 standard deviations of the observed traffic and 1/2 to 1/3 the width of the localizer course. The width of the suggested AVOSS corridor is defined by the following equation, subject to a minimum width of 300 feet. In this equation D represents the distance from the landing runway in units of feet.

$Width = 300,$ Within 2816 feet from the runway.

$Width = 300 + 0.02539(D - 2816),$ Beyond 2816 feet from the runway.

Table 1 - AVOSS Corridor Width

Position	TERPS	Reference 1	Lincoln ASR	ILS	AVOSS
Runway Threshold	1000 ft	300 ft	N/A	700 ft	300 ft
Middle Marker	1842 ft	300 ft	N/A	929 ft	300 ft
2 NM from runway	4633 ft	N/A	319 ft @ MEM 352 ft @ ORD	1689 ft	580 ft
5 NM from runway	10084 ft	N/A	532 ft @ MEM 499 ft @ ORD	3174 ft	1000 ft

Table 2 shows the altitude of the TERPS obstacle floor relative to runway elevation and glide slope (GS), the ILS glide slope limits, and a recommended AVOSS corridor floor. The above ground altitudes are referenced to the runway elevation, not necessarily the local terrain elevation. The AVOSS corridor floor is specified both as a distance above runway elevation and below the glide slope. The AVOSS floor extends to the ground at the runway and out to a distance where the glide slope height is 200 feet. In this region only lateral transport will be used by AVOSS to estimate wake transport times. Beyond this distance from the runway the AVOSS corridor floor rises at a constant gradient. This gradient results in the floor being 200 feet below glide slope at the middle marker increasing to 400 feet below glide slope at a distance of 5 miles from the runway. The suggested AVOSS corridor floor is also always below an altitude corresponding to full scale glide slope deviation. In the region beyond the middle marker, assuming a 3 degree glide slope, the AVOSS corridor floor distance below the glide slope is

$$200 + 0.00725(D - 2816)$$

The corridor floor distance above the runway elevation is

$$0, \quad \text{Within 2816 feet from the runway.}$$

$$0.04515(D - 2816), \quad \text{Beyond 2816 feet from the runway.}$$

Table 2 - AVOSS Corridor Floor

Position	TERPS Limit	Reference 1	ASR	ILS Limit	AVOSS Limit
Runway Threshold	0	N/A	N/A	40 AGL 12 below GS	0 AGL 52 below GS
Middle Marker	57 AGL 143 below GS	N/A	N/A	153 AGL 47 below GS	0 AGL 200 below GS
2 NM from runway	255 AGL 435 below GS	N/A	N/A	528 AGL 161 below GS	422 AGL 267 below GS
5 NM from runway	710 AGL 935 below GS	N/A	N/A	1260 AGL 385 below GS	1245 AGL 400 below GS

Table 3 summarizes the suggested AVOSS corridor dimensions and the time required for a vortex to transport vertically and laterally outside the corridor at two different translation speeds. An initial vortex pair spacing of 100 feet is assumed for computing the lateral transport time. The table is for illustration only and does not include many factors that will be included in the actual AVOSS, such as

changes in vortex drift rate at various altitudes and assumed flight technical error on the part of the generating aircraft.

Table 3 - AVOSS Corridor Dimensions and Example Transport Times

<u>Position</u>	<u>Corridor Width, feet.</u>	<u>Corridor Floor, feet below glide slope</u>	<u>Lateral Transport Time at 10 knot drift, s.</u>	<u>Vertical Transport Time at 200 foot/minute sink rate, s.</u>
Runway Threshold	300	N/A	12	N/A
Middle Marker	300	200	12	60
2 NM	537	267	19	80
5 NM	1000	400	33	120

The takeoff case presents additional challenges for the corridor concept in that the altitude profile of departing aircraft vary widely, as opposed to the precise altitude profile of an aircraft during an instrument landing system (ILS) approach. This factor may be accommodated in several ways by AVOSS. One is to establish a takeoff corridor to accommodate expected variations in aircraft liftoff point, climb gradient, and departure vectors. This would make the takeoff spacing criteria aircraft pair specific since a range of expected climb gradients can be predicted for each aircraft type. Another approach is to ignore the sinking motion of the vortices and depend on lateral transport and assigned departure headings that send lighter aircraft upwind of the heavier aircraft. This would require close coordination with ATC procedures. Yet a third method is to ignore vortex transport and depend only on the decay predictions. Evaluation of these techniques will be made during AVOSS design.

Operationally Acceptable Vortex Strength Definition Requirements

The transport rule component of the AVOSS system is not dependent on knowledge about wake vortex interaction with the following aircraft. The decay rule component of the predictor, however, must predict when the wake of any given aircraft has decayed to an operationally acceptable strength for an encounter by any given following aircraft. While computational models and field observations of wakes can provide the required decay characteristics, industry and FAA consensus will be required to fully set the thresholds of "acceptable" encounters. An example of an acceptable encounter would be a B747 type aircraft encountering the wake of a small general aviation propeller driven aircraft.

An operationally acceptable vortex strength definition has three components. The first is an identification of factors that define the influence of a wake encounter on the operation of an aircraft. These include roll moment generation as a percent of the roll control authority of the aircraft, induced roll rates and accelerations, maximum induced bank angles, or deviations from the localizer, glide slope, or intended touch down location. One example of this type of factor identification is described by reference 10. Piloted simulations of a Learjet and a B707, both during visual and instrument approaches, were used to determine a factor that correlated with pilot opinion of the hazard. Of three factors examined, roll acceleration, roll rate, and maximum bank angle, the maximum bank angle showed the best correlation. In this study the pilots tolerated large bank angle excursions in visual conditions but very limited excursions in instrument tasks. During instrument approaches, a hazard boundary derived from both the B707 and Learjet runs suggested a 7 degree limit at 200 feet above ground increasing to about 10 degrees at 350 feet. The suggested bank angle limit remained constant above 350 feet. It is important to note that the study concerned encounters with hazardous

vortices, while the present study must ask for the vortex intensity that is operationally acceptable to encounter during an ILS approach to minimums or an autoland. As such the boundaries may well be more conservative than the ones suggested above or may have additional constraints such as induced touchdown dispersion. An initial suggestion will be that any vortex that produces forces and moments on the following aircraft, that are similar in magnitude to the forces and moments induced by routinely encountered levels of turbulence, are operationally acceptable.

The second component of an operationally acceptable vortex strength is to define characteristics of vortices that are predictable from knowledge of the generating aircraft specifications and are observable by remote sensors. Either total circulation or average circulation of the vortex over a distance comparable to the wing span of following aircraft have been suggested and quantified in the past. Nearly all prior works rely on some form of a circulation prediction to quantify the strength. Two difficulties of this approach is that the circulation value is not trivially computed from sensor observations and the effect on a following aircraft also depends on the spacing of the cores relative to the span of the follower. For example, if the core spacing of two vortices is $1/3$ the span of the encountering aircraft then any significant encounter will include the opposing circulation of both vortices. The maximum rolling moment that can be induced will be much less than if the following aircraft span were entirely immersed in one of the two vortices. An advantage of total circulation is that an estimate of this parameter can easily be made from knowledge of the generating aircraft weight, wing span, and speed. Another defining characteristic of a wake flow field, suggested by Dr. Bowles but not yet evaluated, is to compute the maximum torque on a reference "flat plate" immersed in the field. This would be equivalent to a second-moment computation of the observed vertical velocity of the wake field. This should have advantages from a computational point of view, but care is needed to scale this factor with estimates of initial wake strength and the effect on various following aircraft.

The third component of an operationally acceptable vortex strength definition is to define the transfer function between the observable characteristic of the wake and the chosen aircraft impact factor. For example, if total circulation and core spacing is chosen as the vortex observable characteristic, and this is mapped onto bank angle upsets using the wing span of the following aircraft, then a map of acceptable circulation values to aircraft span ratios may provide the AVOSS decay rules with the required acceptable vortex strength definition. Work is currently ongoing at NASA Langley and Ames Research centers, using combinations of analytical, wind tunnel, and flight test techniques to develop and validate tools that predict the dynamics of aircraft wake encounters. Industry and FAA Flight Standards involvement will also be required to provide the appropriate consensus on the results.

Weather Subsystem Requirements

While the core of the AVOSS system is the predictor subsystem, the predictions and system effectiveness will only be as good as the nowcasts provided by the meteorological subsystem. The specific requirements of the weather subsystem will be determined as ongoing predictor algorithm research defines the critical atmospheric parameters that effect wake transport and decay and the measurement accuracy required. Initial requirements for this subsystem can be derived from the AVOSS system concept and previous wake studies. The predictive element of AVOSS places a predictive requirement on the weather subsystem. Separation criteria predictions are required before the aircraft approach, requiring 20 to 50 minute weather state predictions. Since no weather system can be expected to precisely predict winds or temperatures in advance, the system must also specify the confidence intervals for each predicted weather parameter.

The requirement to protect the approach and immediate departure corridors also calls for a spatial domain for the weather predictions. Knowledge of atmospheric state is required along each approach path from the outer marker to the runway. This may require atmospheric state information in a region roughly six miles (11 km) in length and from the surface to the glide slope intercept altitude. Two factors may make this requirement more feasible than it may at first appear. First, a

hypothesis to be tested in the AVOSS development research is that the quality of data required at the higher and more distant locations will not be as high as the quality required near the airport. This would be the case, for example, if vortices can be shown to consistently sink below the protected corridor floor in all but a small subset of meteorological conditions. In this case parameters required to predict decay and lateral transport might not be required at those altitudes. When the conditions that may prevent or dramatically slow vortex sinking are detected then the default spacing criteria may be imposed.

A second factor that may simplify the meteorological subsystem requirements is the use of averaging periods and statistical processes. For example, there will be no attempt to predict the actual wind that any single vortex would experience at a later time. Instead the mean and standard deviation of the winds over a suitable interval will be used for the predictor algorithm. As the averaging interval increases in a homogeneous atmosphere, the spatial domain of validity of the measurement or prediction should improve. With 10 to 15 minute averaging intervals, the wind measured above the airport may be a very good approximation to the wind several miles away. Such would not generally be the case in a non-uniform environment with significant variations in terrain type or with land-sea interfaces. Relatively simple instruments, such as an acoustic sodar tested at the Memphis International Airport in November and December of 1994 can also provide frequent updates and variations in wind aloft. The instrument tested provided 10 minute wind averages at 20 meter resolution from 20 meters above the surface to about 300 meters, even during high noise level traffic surges. Large scale atmospheric phenomena such as gust fronts, sea breezes, and convective storms will also create significant horizontal variations in the weather state. Some technique is required to detect and advise AVOSS that such an event is or will be affecting the approach corridor so that default spacing or other spacing adjustments can be made. The Integrated Terminal Weather System (ITWS) program (reference 11) under development by the FAA and MIT Lincoln Laboratory could be integrated with the AVOSS to provide this information as well as nowcasts of the basic weather state variables.

Finally, predictable changes in the planetary boundary layer occur in the morning and evening hours which affect stratification and the low altitude wind structure. Due to the need to adjust traffic flow in advance of the weather change, some prediction capability for this effect must be included. This is particularly critical in the evening when the formation of a temperature inversion may reduce surface winds and tend to increase wake separation requirements.

Given the above information and evidence gained from previous and ongoing wake behavior studies, the following initial requirements for the weather system are suggested. The information is needed over an altitude range from the surface to the glide slope intercept altitude and both mean and variance of items 1 through 3 are required.

1. Wind vector as a function of altitude.
2. Temperature or potential temperature profile.
3. Turbulence statistics over the same altitude range with emphasis on accurate data at low altitudes (surface to 500 feet).
4. Synoptic scale event detection.
5. Planetary boundary layer change prediction.

Wake Vortex Sensor Subsystem Requirements

Although various capability levels of AVOSS may be implemented, some of which would not require a wake vortex sensing subsystem, the AVOSS concept includes a wake sensor. As is the case for the weather subsystem, only general sensor requirements can be stated. Detailed sensor requirements will be defined during the course of the research and development. The sensor subsystem is included for several purposes:

1. Provide a safety backup for erroneous wake predictions.
2. Provide actual wake transport and decay value feedback to the prediction algorithm.
3. May provide limited atmospheric state data.

To be operationally useful to the AVOSS system the sensor must be capable of detecting, tracking, and quantifying the strength of wakes. Operation should be highly reliable and automated, with appropriate self tests. The tracking domain should cover the protected corridor and the sensor system should continue to scan for vortices after exiting from the corridor to accommodate the potential for a vortex that bounces or changes lateral drift direction as altitude is lost. Quantification of vortex strength is required for the decay prediction feedback. Strength is yet to be defined operationally, but could involve either an average angular momentum calculation or a simpler vertical wind second moment over a specified scale length.

Figure 4 shows a concept for the use of position and strength feedback. As time of day progresses the predictor algorithm will produce an estimate of transport time and decay time at various windows on the approach path. The predictor will also estimate the uncertainty in the prediction and provide an appropriate value to ATC that includes a buffer. The sensor system will provide actual transport and decay times to the predictor so that the buffer and values provided to ATC can be adjusted whenever the actual data deviates from the predicted. With appropriate buffer size choices this adjustment will occur before any aircraft are exposed to a potential hazard. In the sudden event of a vortex persisting much longer than expected a message can be provided to ATC to command a go-around procedure for the following aircraft. Great care in design will be required to minimize this type of event. Other uses of the sensor data would be to allow AVOSS to default to standard separation criteria when specified prediction errors or variations in successive vortices develop.

There is currently no evidence that a single point measurement, at the middle marker for example, would suffice for a safety sensor. Atmospheric stratification could potentially lead to accurate predictions at one altitude and large prediction errors at nearby altitudes. The volumetric domain of a wake sensor will be defined based on the criticality of prediction errors at each location and the confidence of predictions. Operational evidence (reference 8) and vortex sink characteristics suggest that the most critical domain for protection will be at relatively low altitudes close to the airport environment, perhaps from the runway threshold to a location slightly beyond the middle marker.

The wake vortex sensor subsystem will be required to operate both in visual and in instrument meteorological conditions. The sensor or sensors will not be required to operate in conditions where accurate wake predictions are not likely to be achieved or where the wake is not likely to be the primary constraint in airport operations. Examples of these conditions include convective storm activity, extremely strong winds, heavy snow or freezing rain. The default vortex spacing criteria may be applied during these periods.

AVOSS Operational Integration

The AVOSS concept described above will be validated for operational readiness and integrated into automated and manual ATC systems. This will require interfaces beyond the minimum required for experimental testing. The interfaces can be divided into three classes, those required for operational AVOSS control, for matching the AVOSS output to the ATC system expectations, and for operational safety and redundancy.

Operational control of AVOSS may be required to accommodate the wide variety of operations conducted. Since minimum vortex separation operations will require some knowledge of expected aircraft position, for the application of transport based separation, it may be advantageous to disable AVOSS during low traffic periods to increase the flexibility of the system for handling visual approaches. An intermediate capacity increase may be possible in certain weather conditions by using only the AVOSS decay rules and disabling the transport rule component of the predictor subsystem. This would permit unlimited curved visual approaches but would likely result in a lower capacity gain than the fully operational AVOSS with approaches constrained to the ILS. These controls could feasibly be available to the local tower supervisor.

The match to the ATC system will include definitions of the appropriate wake vortex separation criteria updates to ATC. Specifically the rate at which the updates are made (i.e. once ever 30 minutes or once every 3 hours), the maximum changes permitted between updates (i.e. 10 seconds, 30 seconds, or no limit), the resolution provided (i.e., 5, 10, or 15 seconds) could all be refined for controller and ATC automation acceptance. Due to the statistical nature of the wake predictions and increasing uncertainty in atmospheric state as forecast time increases, frequent updates would increase the maximum potential acceptance rate of the runway. Too frequent updates would also have negative impact on controller workload and possibly create system problems as the traffic flow adjustments ripple back into the center airspace.

The size of the separation matrix and translation into separation distance will also be adjusted for the ATC system in use. Internally the AVOSS will operate with individual aircraft pair types, such as B-727 or DC-10, perhaps with grouping of the small aircraft category. A highly automated ATC system may be capable of directly using this matrix for highly efficient aircraft scheduling and sequencing. A less capable system, or a manual ATC environment, may require that the aircraft be grouped into three or four major groups for actual use. The AVOSS could provide output in this grouped format. All AVOSS provided wake constraints will be time based and indicate the minimum separation time between airplane pairs anywhere on the approach or initial departure path. Planned ATC automation tools can directly use this time matrix for separation, although controller interface issues would need to be addressed. A manual system would require output in a distance format for direct application by the controllers. Operational procedures and aircraft speed at various positions along the approach path must be considered in this translation of time into distance.

The AVOSS interfaces required for operational safety and redundancy may include meteorological and wake sensor self test features, ATC radar beacon data to monitor the actual aircraft spacing, and graceful degradation modes that allow for limited AVOSS operation with some sensors out of service. Specifically the AVOSS will require a subset of ATC beacon data to know the aircraft type generating each wake observed by the wake sensor. Logic for reversion to standard default spacing criteria will be based on the detected weather, sensor self test results, and errors between predicted and observed wake behavior. Definition of these interfaces will begin after initial field experiences with the AVOSS prototype and as decisions are made regarding operational deployment.

AVOSS System Tradeoffs

The general AVOSS concepts outlined above cover a wide range of possible system implementations, ranging from a simple system that advises a manual ATC system when a specific reduced separation matrix can be used to a multiple sensor system interfaced to an automated ATC system to optimize spacing between individual aircraft pairs. Figure 5 suggests four possible wake system implementations that vary in cost and capability. At one extreme (upper row of figure 5) a static separation matrix determined from a large matrix of aircraft, potentially with one matrix element per aircraft type, can be collapsed into a 3 to 5 category system for manual ATC use. NASA Langley has taken this approach in response to a FAA request for a scientific basis for revised separation standards and aircraft classifications. No dedicated weather or wake sensors would be required for this system, and this is considered to be the "default" AVOSS spacing when weather conditions are changing too rapidly for accurate dynamical wake predictions. A fully automated ATC system could use the full separation matrix for more efficient operations. The lower row in figure 5 represents dynamical spacing interfaced to either a manual or an automated ATC system. The manual ATC system would employ a relatively simple procedure that provides for a fixed, reduced separation matrix under certain weather conditions. An example of this procedure would be to allow less than current standard spacing between all large and heavy aircraft pairs when the atmospheric conditions permit. Dynamical separation standards require a dedicated weather subsystem and, for maximum capacity, a dedicated wake sensor subsystem. The level of AVOSS complexity to be applied at a given airport will be a function of the capability of the ATC system at that facility and tradeoff studies that show the capacity gain expected with various AVOSS levels. Factors which must be considered include:

1. The capacity impact of increased uncertainty buffer sizes required by the lack of a wake vortex sensor. The lack of a wake sensor would likely restrict capacity reductions to a smaller subset of weather conditions and increase the uncertainty in the remaining conditions.
2. Capacity gain benefits compared to cost of improved meteorological subsystem and more accurate atmospheric state predictions. Relatively inexpensive systems are available to measure the vertical wind profile above an airport and may enable some capacity gains, but do not include forecast capabilities or detection of synoptic scale events. More complex systems such as the ITWS have the potential to maximize the AVOSS utility.
3. Capacity gain variations with use of decay only rules or wider protected corridors. If the protected corridor concept is not acceptable in certain situations the AVOSS must depend only on vortex decay, which may severely restrict the utility of the system. If the size of the protected corridor is increased, for example to a width corresponding to full scale localizer tracking error, then increased spacing will be required to allow for the greater drift distance of the vortices.
4. Overall airport capacity gain based on actual traffic schedules and climatology. Simulations should be accomplished for at least some of the potential AVOSS airports to estimate annual capacity improvements. This will require knowledge of the traffic mix and time of day for capacity limited operations and climatology data. The ability to accomplish this simulation will be limited by the lack of detailed climate data at airports. Currently only basic data such as surface wind and temperature are collected. A full AVOSS simulation would include vertical wind structure and stratification, which is only archived in a few research programs such as the NASA/Lincoln Laboratory program at Memphis to be discussed below.

Current Research Activities

The NASA is addressing the development and demonstration of a prototype AVOSS through a combination of analytical, wind tunnel, field and flight tests. Critical activities underway include the following.

Numeric Wake Vortex Modeling

The Terminal Area Simulation System (TASS) large-eddy simulation code of reference 12, proven highly effective in the successfully completed NASA/FAA wind shear program, is being modified to model the effect of various atmospheric conditions on the behavior of aircraft vortices. Modifications include the required wake initialization routines, options to turn off cloud microphysical processes to speed execution time, and post-processing software to diagnose vortex core location and strength. A related effort is developing the ability to model the evolution of the planetary boundary layer (PBL) with changes in sun angle, cloud cover, and terrain (reference 13). Both 2-dimensional and full 3-dimensional modeling of wake behavior are being conducted. Emphasis will be placed on validation of the model behavior against observed wake data prior to using TASS for AVOSS predictor algorithm development. Following validation of TASS, parametric studies will be performed to quantify the effects of stratification, wind speed and vertical shear, and various turbulent scale lengths on the transport and decay of the vortices from various sized aircraft. Once TASS is validated within a given envelope of weather and terrain conditions, these parametric studies should provide more information than could be feasibly gathered from field experiments where multiple factors are usually changing with each observed wake and a limited subset of possible atmospheric conditions can be expected to occur. TASS results will be useful not only for predictor algorithm development, but also as numeric simulation data for developers of candidate wake vortex sensors.

Field Measurements of Aircraft Wake Vortices

Crucial to the validation of TASS, prediction algorithm development, and full system testing and demonstration is a field effort sponsored by NASA Langley and conducted by the MIT Lincoln Laboratory (reference 14). This field effort serves multiple purposes:

1. Provide a comprehensive data collection suite to gather meteorological, aircraft, and wake data at a major airport.

2. Provide the above data for validation of wake models and direct use by predictor algorithm developers.
3. Establish the required field facilities and system interfaces for predictor algorithm and AVOSS prototype testing and demonstration.
4. Since the Lincoln Laboratory is typically utilized by the FAA to design and harden systems, such as the TDWR and ITWS, for actual field implementation, technology transfer is aided through early teaming between NASA, the FAA, and Lincoln.

The Lincoln effort has established a facility at the Memphis International Airport that provides the most complete wake vortex data facility established to date in an operational setting. Aircraft wake vortex data was collected with a 10.6 micron continuous wave laser mounted in a mobile van. The van could be driven to various airport locations as runway operations changed or to collect data at different airplane crossing altitudes. The lidar was implemented with real-time wake vortex identification and tracking algorithms to optimize data quality (reference 15).

A 150 foot tower measures wind direction, temperature, and humidity at five elevations. Solar flux, soil temperature, and soil moisture are measured for correlation with the atmospheric boundary layer characteristics and validation of PBL models. A radar profiler with a radio acoustic sounding system (RASS) provided winds aloft from approximately 100 meters AGL to about 2500 meters AGL with a vertical resolution of 100 meters. Winds were provided with a 25 minute averaging period. The RASS provided temperature up to about 1000 meters AGL at a 5 minute averaging period. The profiler alternated radar and RASS operation such that each hour two radar profiles were provided separated by two temperature profiles. Also employed was an acoustic sodar that provided 10-minute average winds with a vertical resolution of 20 meters from an altitude of 20 meters up to about 300 meters AGL. Dedicated rawinsonde balloon launches were made from the airport during the tests.

A NASA Langley OV-10 aircraft also participated for a limited period during the tests by collecting atmospheric wind, temperature, and humidity data along the approach paths. The purpose of the OV-10 flights was to provide data to answer questions concerning the spatial variability of critical atmospheric parameters. This information is needed not only for the AVOSS design but to better correlate lidar wake measurements with local weather. The meteorological tower and profilers were all located near the south end of the airport, between the parallel north-south runways, while the lidar typically operated at the north side of the airport or about 1 mile south of the airport.

Lincoln also collected extensive aircraft data for the transports being observed through agreements with the major transport operators at Memphis. The operators provided the actual approach weight of each aircraft observed and information on flight procedures required to estimate flap setting from airspeed and weight. Air Traffic Control beacon data, collected and maintained by Lincoln, provides the altitude, aircraft type, and ground speed of each aircraft crossing the Lincoln laser facility. Lincoln uses this data and the meteorological data to estimate the aircraft airspeed and correlate individual arrivals to the operator-provided weight data. This processing provides detailed information on the aircraft generating each observed wake.

The initial Memphis deployment occurred between November 15 and December 14, 1994. During this deployment all systems were operated together for the first time and the lidar wake tracking software was refined and brought to an operational status by Lincoln. Approximately 600 aircraft wakes were observed, with about 100 observed with the lidar tracking algorithms functioning. By working nearly around the clock, Lincoln researchers were able to collect data during late evening traffic surges while boundary layer conditions were slowly changing, as well as daytime operations. Data reduction, analysis, and preparation for an August 1995 deployment is in progress.

Predictor Algorithm Development

With the initial Memphis field experiment complete and early TASS validation work nearing completion, work is beginning on the prediction algorithm development. The starting point for the

algorithm work is prior work such as that described in references 1, 16, and 17. Many of these past efforts provide some insight into certain aspects of vortex transport and decay but do not cover the entire domain. Limited data is available to describe transport and decay of vortices at altitudes that are above ground effect. Little available data exists to specify transport or decay of vortices created in ground effect. Beginning with available data an initial version of a predictor algorithm will be developed for test during the 1995 Memphis wake vortex field tests. This predictor algorithm will provide only the transport time (no decay information) for the wakes of several aircraft types out of ground effect. Meteorological data collected at Memphis will be downloaded at Langley on a daily basis and used to run the predictor algorithms. The predictions will then be compared to the lidar tracking data when that information becomes available after deployment. Benefits of the early predictor testing are expected to include hardware and software interfaces for ingesting near-real time meteorological data as well as an evaluation of the adequacy of simple transport models and the robustness of predictions in different weather types. Each year a more advanced predictor algorithm will be tested. Decay modeling, ground effect altitude domains, additional aircraft types, additional weather domains, and feedback from wake sensors will be added as the knowledge is gained. The goal is to provide a full-featured predictor algorithm, with real-time interfaces to weather, wake, and ATC beacon sensors by 1999 for an end-to-end system evaluation and industry demonstration.

Operationally Acceptable Wake Vortex Strength Definition

Analytical, wind tunnel, and flight work are in progress to define the sensor observable characteristics of wake vortices that may be used to define the operationally acceptable strength for a wake encounter. These efforts are described in reference 18. This strength definition is required for the decay component of the predictor algorithms as well as to support other FAA initiatives to revise current aircraft classifications and separation standards. Strong industry consensus is also required to implement a system that permits vortex encounters at some strength level.

Wake Vortex Sensors

Efforts are in progress at Langley to develop and demonstrate ground based sensor technologies to support the AVOSS concept. Both radar and laser technologies are being examined for operational feasibility. A technology selection is scheduled to take place in 1996. The selected technology will be further developed and fielded as early as 1997 for field tests and initial AVOSS integration. The goal of the sensor development effort is to provide the wake sensor subsystem requirement for an AVOSS prototype demonstration in the 1999 time frame.

AVOSS/ATC Integration

Coordination has begun and will continue between the AVOSS development effort and FAA Air Traffic/Flight Standards as well as the NASA Ames development of the Center-TRACON Automation System (CTAS). This coordination is essential to match the output of AVOSS, in resolution, frequency, and confidence, to the expectations and needs of manual and automated ATC systems. The coordination is also required to ensure an operationally acceptable system from the perspectives of ATC procedures and accommodation of off-nominal conditions such as missed approach procedures or engine-out reduced climb gradients on departure.

Summary

A concept is presented for the development and implementation of a prototype Aircraft Vortex Spacing System (AVOSS). The purpose of the AVOSS is to use current and short-term predictions of the atmospheric state in approach and departure corridors to provide dynamical, weather dependent separation criteria to ATC facilities with adequate stability and lead time for use in establishing arrival scheduling. The AVOSS will accomplish this task through a combination of wake vortex transport and decay predictions, weather state knowledge, defined aircraft operational

procedures and corridors, and wake vortex safety sensors. Work is currently underway to address the critical disciplines and knowledge needs so as to implement and demonstrate a prototype AVOSS in the 1999 time frame.

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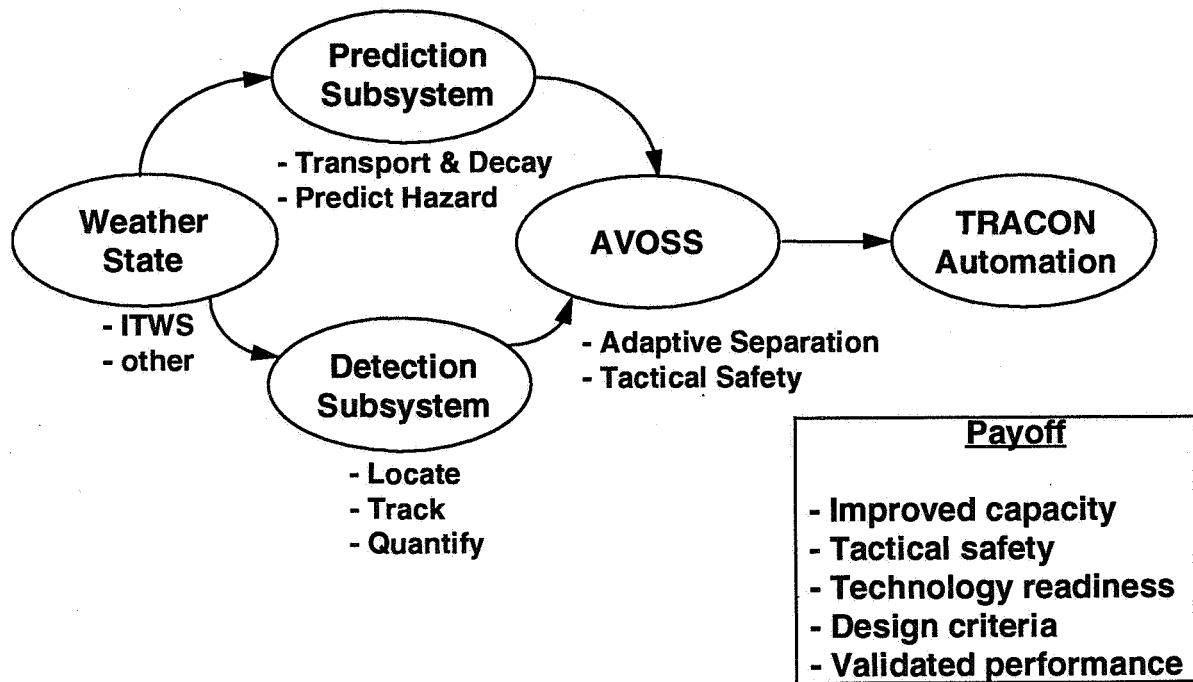


Figure 1 - AVOSS System Concept

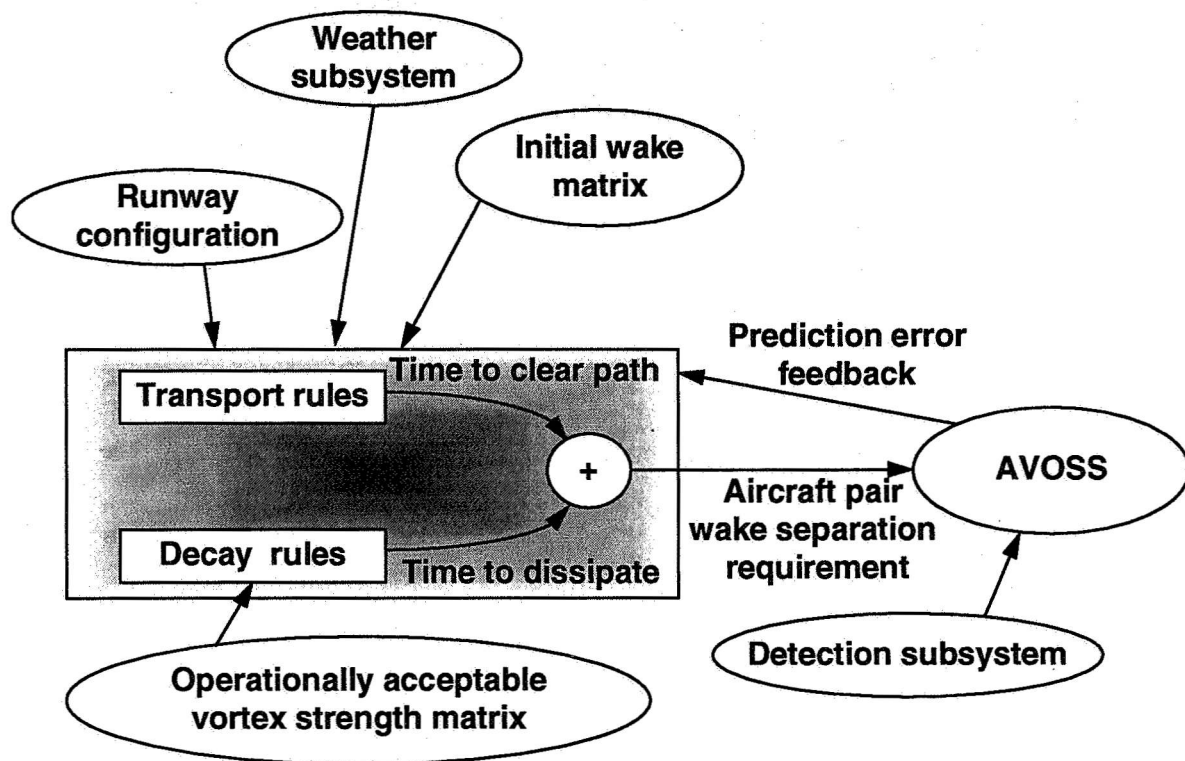


Figure 2 - AVOSS Predictor Subsystem

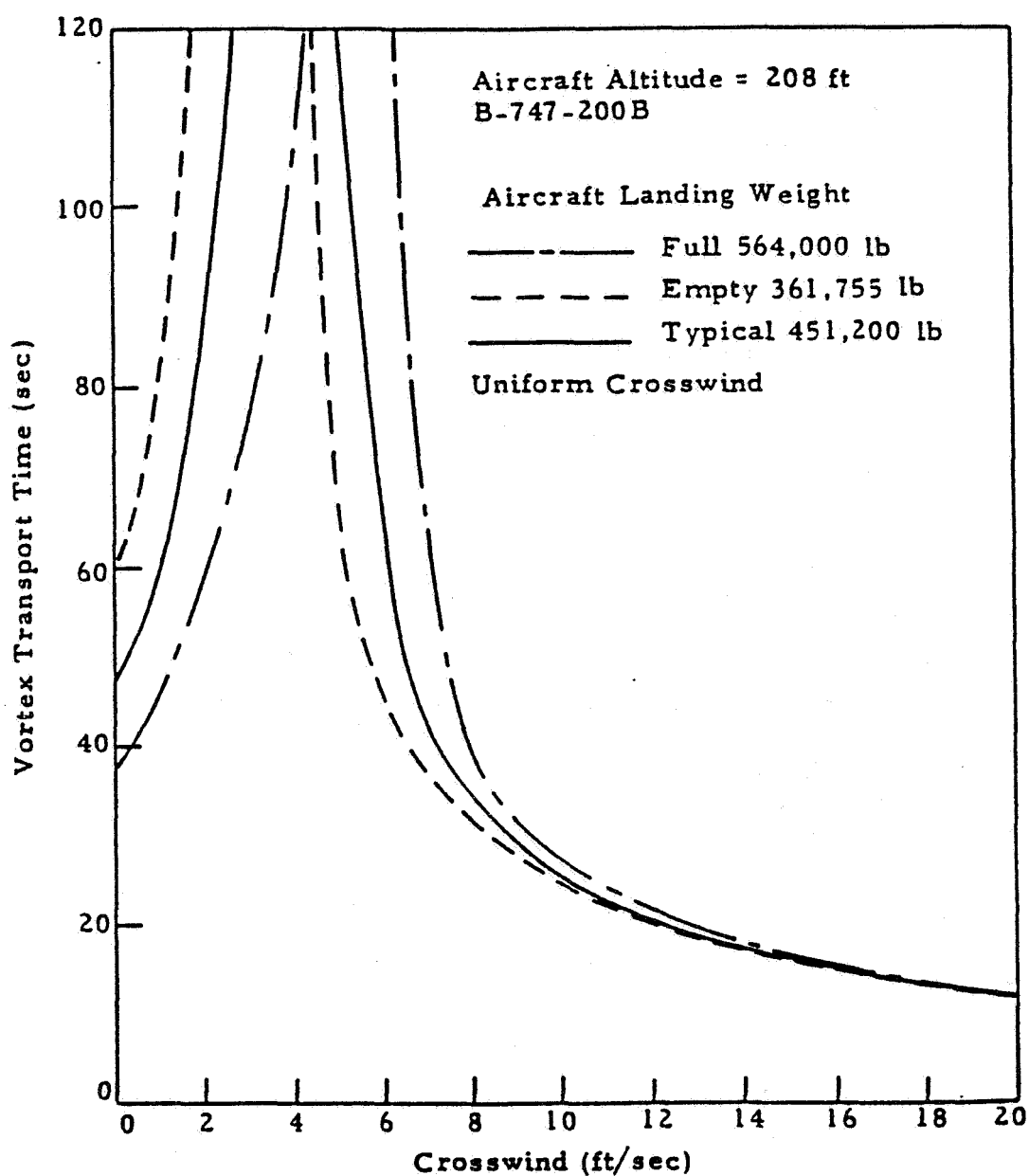


Figure 3 - Analytical Prediction of Time Required for a Vortex to Clear an Approach Corridor - from Reference 1

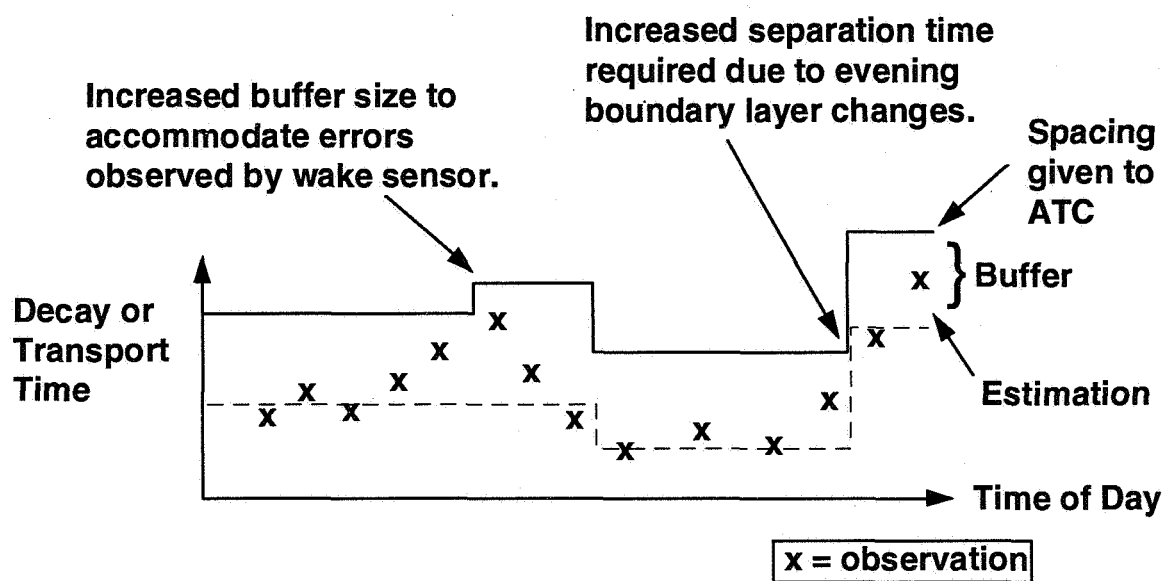


Figure 4 - Wake Vortex Sensor Feedback.

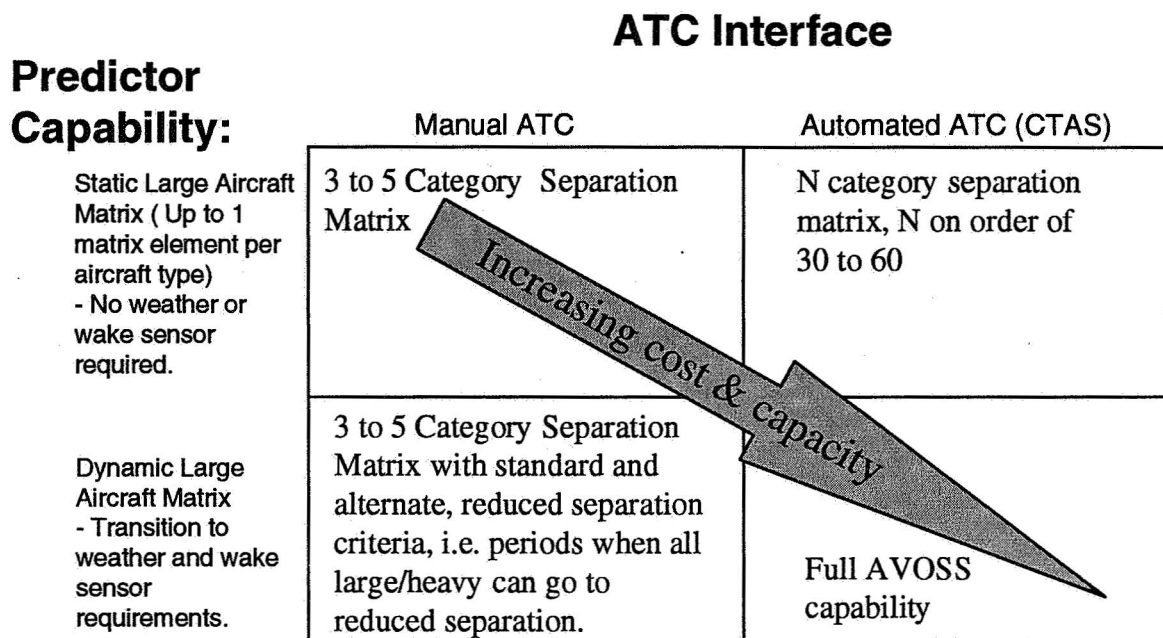


Figure 5 - Wake Vortex System and ATC Interface Capability Levels

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13. ABSTRACT (Maximum 200 words) A concept is presented for the development of a prototype Aircraft Vortex Spacing System (AVOSS). The AVOSS development is being performed by NASA Langley as an element of the Terminal Area Productivity (TAP) Program, and in support of the FAA Integrated Wake Vortex Program Plan. The purpose of the AVOSS is to provide dynamical, weather dependent wake vortex separation criteria to ATC facilities with adequate stability and lead time for use in runway scheduling. The AVOSS will accomplish this task through a combination of wake vortex transport and decay predictions, weather state knowledge, defined aircraft operational procedures and corridors, and wake vortex safety sensors. With the appropriate interface to planned ATC automation, spacing can be tailored to specific generator/follower aircraft types rather than several broad weight categories of aircraft. In a manual ATC environment, the AVOSS may be used to determine when reduced separation standards may be used. Work is currently underway to address the critical disciplines and knowledge needs to demonstrate a prototype AVOSS in the 1999 time frame. This document describes the concept and candidate form of an operational AVOSS system, system ground rules and requirements, research needs, and the development efforts being followed.				
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